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NAVAL POSTGRADUATE SCHOOL

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Beaked Whale Anatomy, Field Studies and Habitat Modeling

by

John Hildebrand

November 2007

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13. ABSTRACT ***(maximum 200 words)***

Results of field studies of beaked whales in the Gulf of California for December 2004-December 2006 are described. The goal is to determine the range of sound produced by beaked whales and to investigate beaked whale behavior and habitat. A minimum of 17 cetacean species (12 toothed and 5 baleen whales) were observed in 147 sightings. The proportion of sighted toothed whales and baleen whales was 67% and 32%, respectively.

A comprehensive formulation for finite element modeling of biological tissues was developed. The mesh is voxel-based, and is generated automatically from CT scans. CT data from live, frozen, and thawed specimens of *Tursiops truncatus* showed similar results in tissues and organs for the following quantities: geometry, absolute density, and sound velocity. Simulated sound sources placed inside and outside of modeled adult male Cuvier's beaked whale (*Ziphius cavirostris*) revealed pathways for acoustic propagation into and out of the head. The simulations indicated a new "gular pathway" for sound reception. Propagated sound pressure waves enter the head from below and between the lower jaws, continuing toward the bony ear complexes through the internal mandibular fat bodies.

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Beaked Whale Anatomy, Field Studies and Habitat Modeling

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Contract Number: **N00244-06-C-0030**
Project Title: **Beaked Whale Anatomy, Field Studies and Habitat Modeling**
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Executive Summary

This project addresses two tasks related to the study of beaked whales. Field studies are documented in the Gulf of California, which is an exceptional habitat for the study of beaked whales. The goal of this work is to determine the range of sound produced by beaked whales and to investigate beaked whale behavior and habitat. A minimum of 17 cetacean species (12 toothed whales and 5 baleen whales) were observed in 147 sightings. The proportion of sighted toothed whales and baleen whales was 67% and 32%, respectively. In total, from December 2004 to December 2006 the southwest Gulf of California represents one of the areas of highest species richness of marine mammals in the world with 16 species of toothed whales and 5 species of baleen whales recorded.

The second task is modeling of beaked whale anatomy, the conversion of anatomy to physical properties, and the use of these in a finite element model of the effects of intense sound. As part of the process of validating our methodological procedures we compared CT data from live, frozen, and thawed specimens of *Tursiops truncatus.* Our study shows that CT scanning produces similar results in tissues and organs for the following quantities: geometry, absolute density, and sound velocity across live and thawed specimens.

A comprehensive formulation for finite element modeling of biological tissues has been developed as part of this research. To address the difficult problem of discretizing anatomical geometries, the mesh is voxel-based, and is generated automatically from common biomedical data sets (e.g., CT scans). A highly efficient parallel finite element code has been written, and an eight processor Linux machine enabled simulations with ~1/2 billion unknowns to be carried out within a matter of days.

Simulated sound sources placed inside and outside of an adult male Cuvier's beaked whale (*Ziphius cavirostris*) have revealed pathways for acoustic propagation into and out of the head. Sound sources located at the left and right phonic lips produce beams that converge just outside the head and slightly right of the midline. This result supports the notion that dual sonar sources interfere constructively to form a sonar beam in front of the animal. The most important questions regarding sound exposure concern the pathways by which sounds reach the hearing apparatus. A 40 kHz planar wave that approaches from in front of the animal may be transmitted through the lower jaw by flexural wave coupling. The simulations also indicate a new "gular pathway" for sound reception. Propagated sound pressure waves enter the head from below and between the lower jaws, continuing toward the bony ear complexes through the internal mandibular fat bodies.

Background

Beaked whales are the most common species that has been associated with mass strandings in the presence of high-intensity ocean sound. This association has raised concerns over their potential sensitivity to high intensity sound sources, such as mid-frequency sonars. The causal factors for beaked whale mass strandings in association with sonar are unclear (Cox *et al.* 2006). The Navy needs to better understand the anatomy, habitat and behavior of beaked whales in order to minimize effects that may be related to sonar operations. This study, through its continued field studies of beaked whales in favorable habitats and development of simulations for sound propagation within the beaked whale anatomy, provides critical information needed to provide a basis for Navy planners and operators to mitigate adverse effects on marine mammal populations.

Beaked whale sound production is an important aspect of their behavior. Passive acoustic monitoring of beaked whale vocalizations may be key both for understanding their occurrence in the marine environment, and also for better understanding of beaked whale potential sensitivity to Naval sonar. Beaked whales are known to echolocate while searching for and capturing their prey (Johnson *et al.* 2004). The echolocation signals of beaked whales are species distinctive and most beaked whale echolocation is frequency swept in character, making these signals distinctive from echolocation signals of any of the delphinids. Cuvier's beaked whale is the primary species involved in mass strandings associated with sonar usage. The peak frequency of Cuvier's beaked whales' echolocation is near 40 kHz. Beaked whales use a frequency upswept echolocation signal when in search mode, making these signals distinctly different from any other known marine mammal sound. Broadband recordings are not available for most of the 20 or more species of beaked whale, thus comparison of echolocation sounds across species is limited by incomplete data.

Cuvier's beaked whale is the most common beaked whale, and it occurs worldwide at latitudes below about 55 degrees. Beaked whale habitat typically is near a pelagic setting. Appropriate sites are at continental shelf edges, deep water islands, or seamounts. The probability of spotting these animals at sea is greatly increased by exceptionally calm conditions, for instance, sea-state 0 or 1. The proper site for a long term beaked whale field study, therefore, has at least these two characteristics: proximity to deep water, and calm weather conditions.

Beaked whales are present in every ocean of the world, but few areas have been identified where they can be easily studied. The southwestern Gulf of California is characterized by a narrow continental shelf and is protected from the conditions of the open ocean. This area has been identified as having among the highest densities of beaked whales anywhere in the eastern Pacific Ocean. This report updates results for our project to study beaked whales in the Gulf of California, an excellent habitat for beaked whales that includes a diverse community of beaked whale species, and which provides excellent conditions for conducting field studies. During FY2004 we initiated a beaked whale field study in the southern Gulf of California, in collaboration with Jorge Urban (Universidad Autonoma de Baja California Sur, La Paz, Mexico). This work was coordinated with Naval Postgraduate School physical oceanographic moorings and CTD measurements spanning the mouth of the Gulf of California. Monthly visual surveys were initiated in December 2004 and were continued until December 2006. During many of these trips, we made opportunistic acoustic recordings of beaked whales and other marine mammals. Likewise, Mark McDonald (Whaleacoustics) assisted with the development of beaked whale automatic detection algorithms. During 2007 a new study site in the northern Gulf of California was investigated to provide a comparison to the southern Gulf of California site investigated during 2005-2006.

Another aspect of this contract is imaging of beaked whale anatomy, the conversion of anatomy to physical properties, and the use of the results of these aspects in a finite element model for the

effects of intense sound. We have conducted studies on the anatomy, physical properties, and finite element modeling of beaked whales, in collaboration with Ted Cranford (Quantitative Morphology Consulting, Inc. and San Diego State University) and Petr Krysl (UCSD Department of Structural Engineering). Our approach is to build models and simulations to investigate the propagation of sound within the heads and bodies of beaked whales. This report updates our progress on imaging and modeling beaked whales in an effort to better understand their sound production, reception and potential impacts due to exposure to sonar.

Objectives

The overall objective of this project is to better understand beaked whale abundance, distribution, habitat, anatomy and physiology, with particular reference to their sound production, reception and sensitivity to sonar. The field data from the Gulf of California help to better characterize beaked whale abundance, distribution, seasonality, and acoustic behavior. One aspect of this work is to develop algorithms for beaked whale automatic detection and classification of beaked whale sounds. Imaging and finite element model simulations within the head of an adult Cuvier's beaked whale help to understand beaked whale sound reception, production, and potential sensitivity to sonar.

Results

We first present results from the past year of collaborative study of beaked whales and other cetaceans in the southwestern Gulf of California. Our study applied both visual and acoustic methods to the study of the distribution and abundance of beaked whales and other cetaceans. The application of these two methods together in the same location is significant for understanding their relative strengths and weaknesses. We have collected an extensive set of visual observations to outline the distribution and abundances of cetaceans. In addition, we have collected new data on the kinds of sounds produced by cetaceans by making acoustic recordings in the presence of visually identified animals.

We collected acoustic data using suspended hydrophones, deployed sonobuoys (hydrophones that transmit recordings by radio to the ship), and sea-floor moored acoustical recording devices. These instruments were deployed in the presence of cetaceans to record underwater vocalizations of known species, and were deployed for longer periods at fixed locations. Data from these instruments were converted to spectrograms (plots of acoustic frequency versus time) and scanned for cetacean vocalizations. Table 1 gives information on the locations for deployment of sonobuoys and high-frequency recording packages (HARPs) as well as the recorded species.

Table 1. *Acoustic recording locations and species present. Sonobuoy types are 57B (onmidirectional), 53D (DIFAR) and 77B (array).*

Lat (N)	**Lon (W)**	**Type**	**Comments**
32 10.20	117 05.14	57B	Fin or sei whale, no calls
31 33.40	116 45.52	77B	Blue whales, D calls received
30 06.41	115 59.69	77B	Blue whales, D calls received
29 43.47	115 48.13	57B	Blue whales, D calls received
28 52.66	115 22.24	57B	near fish aggregation, no calls received
28 17.78	115 07.07	77B	Sperm whale, clicks
28 16.28	115 07.127	57B	no whales heard
25 56.75	113 30.95	77B	Blue whales
25 42.35	113 18.41	57B	*Delphinus sp.*, Whistles & clicks recorded.
24 39.59	112 23.56	57B	*D.capensis*. Whistles recorded
24 10.955	111 46.223	57B	*D.capensis*, baleen whale
23 45.01	111 12.94	57B	*D. delphus*,Whistles recorded
23 00.32	109 24.92	57B	*T.truncates*, Whistles recorded
23 29.67	109 23.92	57B	Humpback
23 55.27	109 34.43	57B	Sperm whales, clicks
23 59.20	109 38.816	57B	faint whistles
24 03.534	109 39.000	57B	*Ziphius cavirostris*, no calls
24 08.21	109 42.89	57B	*T.truncatus*, Many clicks & whistles
24 24.238	109 55.393	57B	*K. breviceps.*, *T.truncatus* in dist
24 19.351	109 57.664	53D	D calls received.
24 12.15	109 55.59	57B	Dolphins (Tt or D.spp)
24 16.501	110 00.343	57B	*T.truncatus*. Whistles, burst pulses
23 34.017	109 19.319	57B	*T.truncatus*. Clicks received
23 39.388	109 23.057	57B	*T.truncatus*
23 43.629	109 28.600	57B	*T.truncatus*
23 46.244	109 34.539	57B	*Mesoplodon spp*
23 54.546	109 38.234	57B	*Mesoplodon spp*
23 57.491	109 39.351	77B	Fin or Bryde's whale
24 03.693	109 40.807	57B	*T.truncatus*
23 52.035	108 51.285	57B	Sperm whale & rough toothed dolphin
23 54.657	108 48.061	57B	Sperm whales
23 53.98	108 46.864	57B	Striped dolphins
23 59.031	108 53.582	57B	Striped dolphins. sperm whale & *tursiops*
23 57.866	109 11.168	57B	*Grampus gresius*
23 52.385	109 17.206	57B	Killer whale pod. sperm whale clicks. *Z.cav.*
23 53.545	109 09.764	57B	*Mesoplodon spp*
23 48.840	109 08.014	57B	*D. capensis*, Sperm whale, Tt
23 44.409	109 19.342	57B	Sriped dolphin
23 45.788	109 22.024	57B	*Z. cavirostris*
23 42.041	109 28.276	57B	*T.truncatus*
23 56.380	109 23.397	57B	Striped dolphins.Whistles
24 03.906	109 29.029	77B	Bryde's whale. No obvious calls.
24 06.261	109 40.906	57B	*Z. cavirostris*
23 44.402	109 35.063	57B	*T.truncatus*
23 49.823	109 37.808	ARP	Pt. Pescadero, various calls

VOCALIZATIONS AND MARINE HABITAT OF BALEEN AND BEAKED WHALES

Gustavo Cárdenas, Jorge Urbán and Alejandro Goméz-Gallardo.

This report represents the third year of uninterrupted search effort for beaked whales, making this study a unique research about this group of cetaceans in the Gulf of California. Beaked whales are one of the least known groups of large mammals world-wide. They are present in every ocean of the world, but few areas have been identified where they can be easily studied. The southwestern Gulf of California is characterized by a narrow continental shelf and is protected from the conditions of the open ocean. This area has been identified as having among the highest densities of beaked whales anywhere in the eastern Pacific Ocean, increasing both the importance of this area like a Marine Mammal Refuge and the interest for the scientific community in the study and conservation of this extraordinary marine system.

OBJECTIVES

1) Generate information about the function of the vocalizations in the behavior of the baleen and beaked whales in their aggregations in the southwestern Gulf of California.
2) Analyze the habitat, behavior and vocalizations of beaked whales.

GULF OF CALIFORNIA STUDY AREA

The Gulf of California (Figure 1) is the only marginal sea of the eastern Pacific Ocean, located between the Baja California Peninsula and northwest mainland México (Castro *et al*. 2000). It is a large evaporation basin, with the free connection to the Pacific Ocean (Roden 1964). Length is about 1000km and average width is about 150km (Santamaría *et al*. 1994). Topographically, the gulf is divided into a series of basins and trenches, a shallow basin to the north, and a sequence of deeper basins to the south, which are separated from each other by transverse ridges (Alvarez-Borrego 1983). Some of these southern basins reach a depth of more than 2500m, like the Pescadero basin (Castro *et al*. 2000). Most of the gulf is characterized by a narrow continental shelf (especially the southwest), except in the north and the Sonora and Sinaloa coasts, as well as in the neighborhoods of the Colorado River delta. Strong, semicontinuous tidal mixing and seasonal upwelling occurs in the central gulf, near the northern islands; northwest winds cause upwelling on the eastern shore during winter and spring; and southern winds cause upwelling on the west coast during summer (Roden and Groves 1959; Badán-Dangon *et al*. 1985). The marked seasonal behavior of the wind is a consequence of the seasonal changes of atmospheric pressure centers in its vicinity and the channel effect of the mountains (Roden 1964; Badan-Dangon *et al*. 1985; Merrifield and Winant 1989).

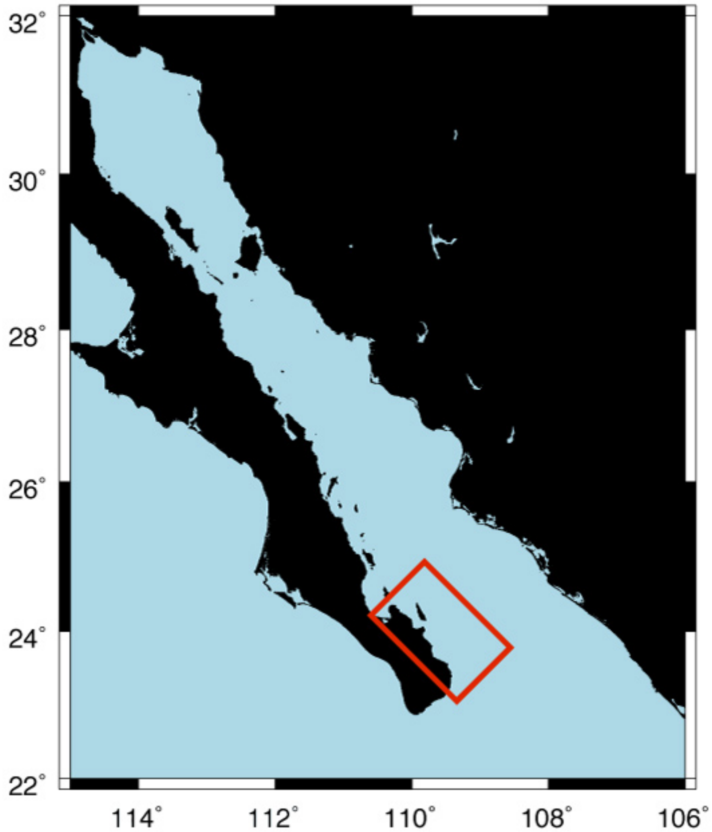

Figure 1. *Beaked whale study area in the southwestern Gulf of California (outlined in red).*

METHODS

Survey effort

Surveys were conducted monthly from January 2006 to December 2006 on a variety of different vessels. This year, no sightings of beaked whales were recorded during research cruises conducted to study humpback whales.

Table 2. *Characteristics of the different survey vessels.*

Size vessel	Name vessels	Length	Platform Height
Small	Yubarta, Hakuna Matata, and Nueva Era	22’	2’
Medium	Amigo	44’	18’
Large	R. G. Sproul	125’	25'

The tracklines for small and medium vessels were done near to the shoreline following a zigzag line. For the large vessel, the transects were done parallel to the coast. Three observers on each vessel scanned for beaked whales with 7x50 handheld binoculars and naked eye when weather and

sea conditions permitted (Beaufort <4). Effort data were collected with locations recorded once a minute on a GPS. Beaked whales seen were approached to confirm species, record location and group size, and to obtain identification photographs.

Cetacean distribution and depth

Distribution and depth of marine mammal sightings were determined by bathymetric and coast line digital maps of the Gulf of California. Both were digitalized for “Eco-regional planning from the Gulf of California and west coast of Baja California Sur Project”, coordinated by *The Nature Conservancy* and *Comunidad y Biodiversidad, A.C.* The data were taken from bathymetric maps of Secretaria de Marina de México and from topographic maps of I.N.E.G.I. (Instituto Nacional de Estadística, Geografía e Informática, México). These maps were produced through geographic information system (Ilwis 3.2 and ArcView GIS 3.2).

RESULTS

Search effort

During 2006 we covered 2334km of trackline in 166 hours over 35 days of search effort. The Los Barriles area was the area most visited (Table 3).

Table 3. *Summary of survey and search effort in the southwestern Gulf of California in 2006. I.C. = Isla Cerralvo; L.F.=Los Frailes; S.J.C.=San José del Cabo.* ***Note:*** *Los Barriles area includes Punta Pescadero.*

Vessel	Date	Search area	Distance (km)	Search effort (hours)
Amigo	29/Jan-02/Feb/06	I.C. – S.J.C.	291.19	20.53
R. G. Sproul	07/Feb/06	L.B. – L.F.	90.01	8.58
Yubarta	26/Feb-02/Mar/06	Cabo Pulmo	28.59	2.99
Yubarta	30/Mar-02/Apr/06	Cabo Pulmo	101.75	6.85
Hakuna Matata	24-28/Apr/06	Los Barriles	147.43	15.33
Amigo	29/May-02/Jun/06	I.C. – S.J.C.	439.08	33.79
Yubarta	29-31/Jul/06	Los Barriles	244.45	14.26
Nueva Era	19-23/Aug/06	Los Barriles	318.38	16.20
Amigo	26-30/Sept/06	I.C. – S.J.C.	402.52	29.83
Yubarta	27-31/Oct/06	Los Barriles	208.29	12.86
Nueva Era	07-11/Dec/06	Los Barriles	62.43	4.73
Total:			**2334.12**	**165.95**

The survey effort of the medium size boats was concentrated between Isla Cerralvo and Los Frailes areas since most of the beaked whale sightings of 2004-2005 were in that area and because of its narrow continental shelf. For this reason, the search effort in the small boats was conducted mainly in Los Barriles area (Table 3). Aboard the *R..G. Sproul*, only one day of February was used to search for beaked whales. In general, transects were done farther from the shore than in 2004-2005 surveys (Figure 2).

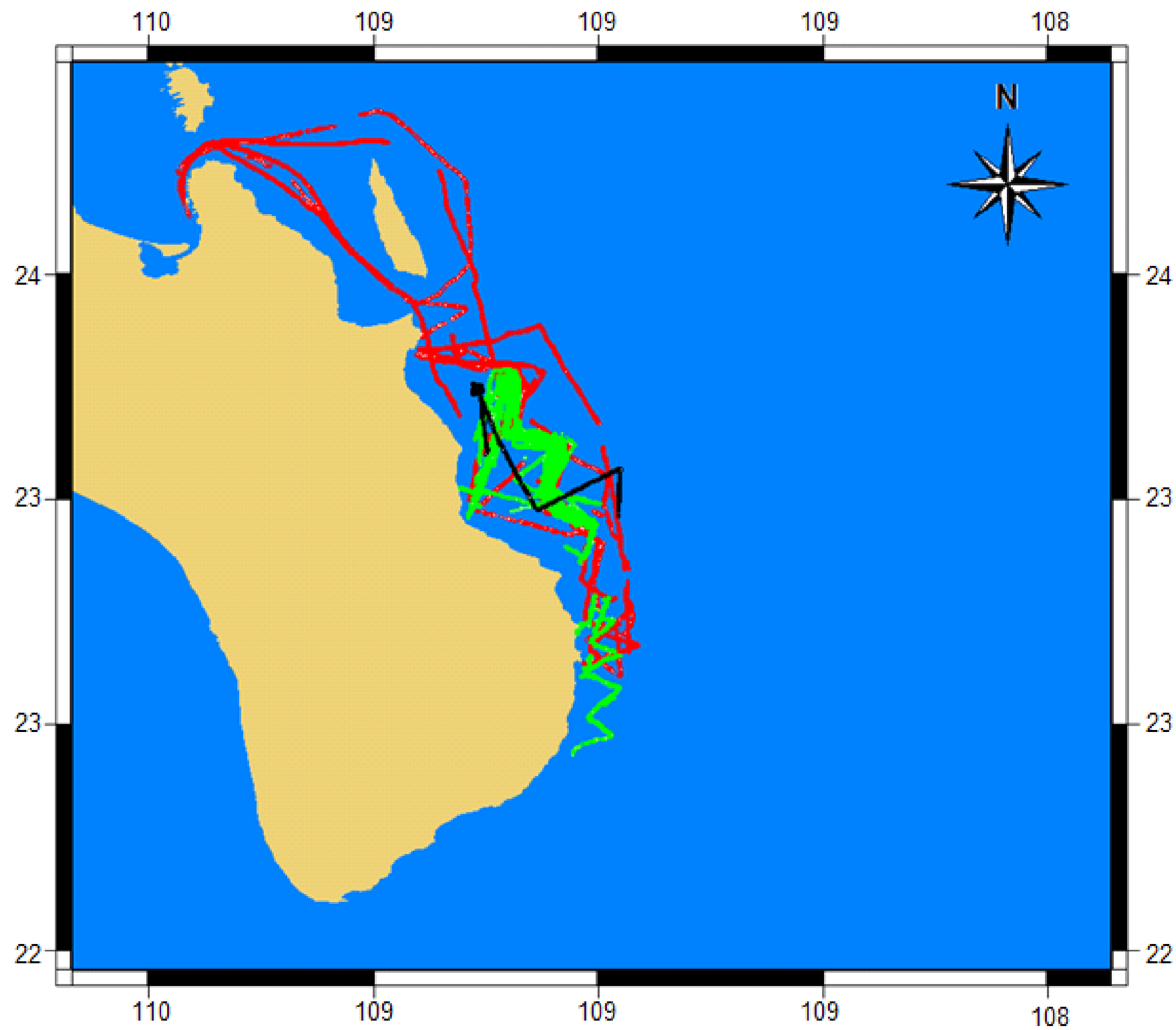

Figure 2. *Survey tracks for different vessels during 2006 in the southwest Gulf of California. Only survey efforts during acceptable daylight sighting conditions with observers on watch are shown. (small, medium and* ***large*** *vessels)*

Sightings and distribution of cetaceans

A minimum of 17 cetacean species (12 toothed whales and 5 baleen whales) were observed in 147 sightings. The sighting proportion of toothed whales and baleen whales was 67% and 32%, respectively. A total of 1981 photographs and 37 biopsies were taken (Table 4).

Humpback whales were the most common of the five baleen whale species sighted. The humpback data will be included to an international collaborative research effort on humpback whales called SPLASH that began in 2004. Data gathered during this project will be part of SPLASH sampling in Mexico, coordinated by UABCS. Identification photographs of humpback whales will be compared and integrated into the collection of identifications from all of Mexico by UABCS and then compared to the entire North Pacific by Cascadia Research.

Table 4. *Summary of sightings of marine mammals in the southwestern Gulf of California in 2006.*

Species	Common name	Total			
Baleen whales:		# sigth.	# ind.	#photos	# biop.
M. novaeangliae	Humpback whale	21	30	145	11
Balaenopterid	Unid. large whale	11	12	0	0
B. edeni	Bryde´s whale	7	10	89	1
B. musculus	Blue whale	5	5	26	3
E. robustus	Gray whale	2	5	57	1
B. physalus	Fin whale	1	1	29	1
Total:		**47**	**63**	**346**	**17**
Toothed whales:					
T. truncatus	Bottlenose dolphin	30	1505	7	0
K. sima	Dwarf sperm whale	24	41	112	0
D. capensis	Long-beaked common dolphin	9	1212	159	0
Z. cavirostris	Cuvier's beaked whale	7	14	217	1
G. griseus	Risso’s dolphin	6	747	217	0
O. orca	Killer whale	4	25	550	17
Delphinid	Unid. Delphinid	4	16	0	0
Kogia sp.	Kogia sp.	3	4	0	0
K. breviceps	Pigmy sperm whale	2	3	0	0
S. attenuata	Pantropical spotted dolphin	2	650	82	0
D. delphis	Short-beaked common dolphin	2	530	2	0
P. crassidens	False killer whale	1	25	46	2
S. bredanensis	Rough-toothed dolphin	1	100	65	0
G. macrorhynchus	Pilot whale	1	100	124	0
L. obliquidens	Pacific white side dolphin	1	20	54	0
Unid. toothed whale	Unid. toothed whale	1	1	0	0
Total:		**98**	**4993**	**1635**	**20**

Note: There are 2 sightings more of unidentified cetacean.

The most common species sighted for toothed whales was the bottlenose dolphin, followed by dwarf sperm whale, long beaked common dolphin, and Cuvier’s beaked whale (Table 4).

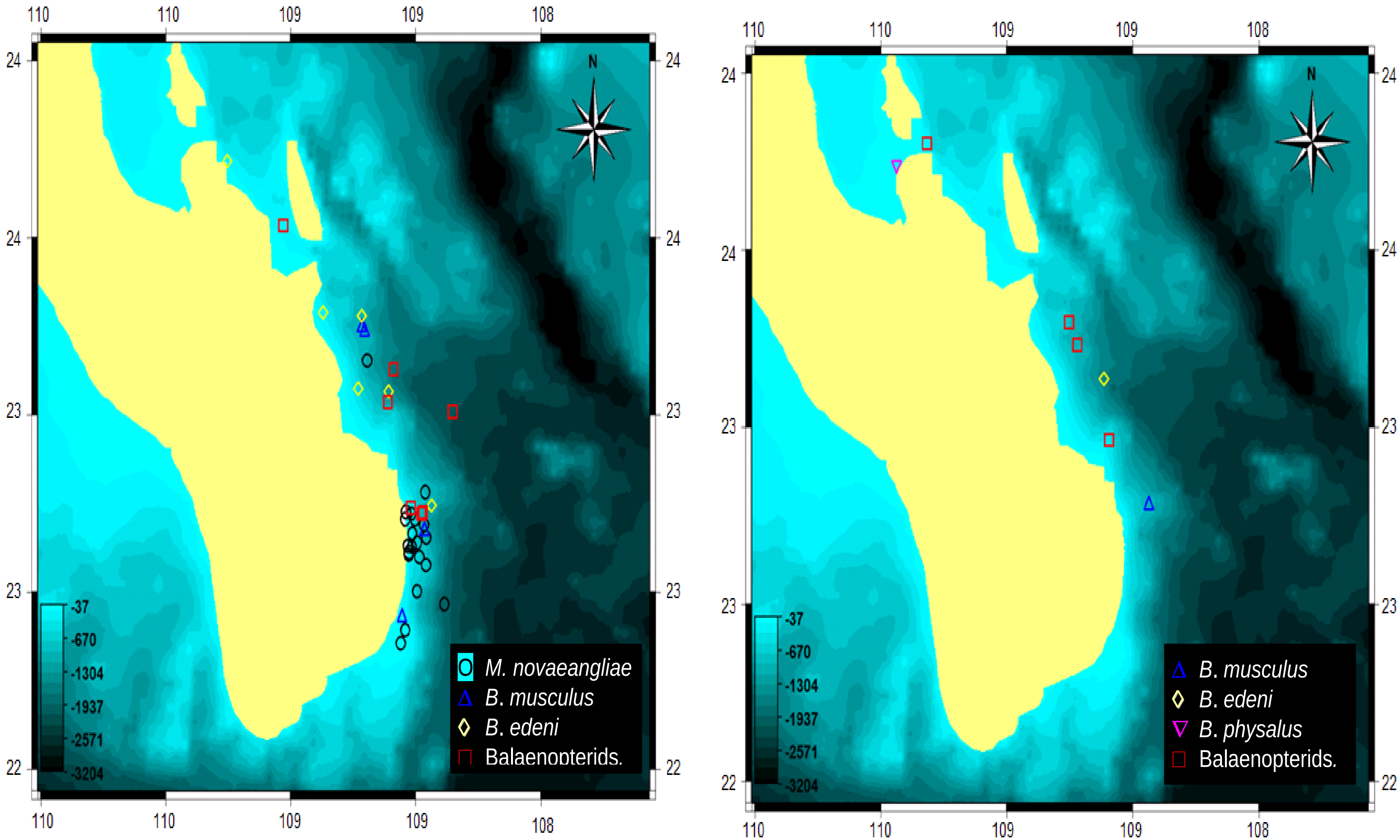

Figure 3. *Winter (left) and summer (right) sightings distribution of baleen whales in the southwestern Gulf of California (2006), and the relation with sea bottom topography. Each symbol represents a single sighting. The depth scale is in meters.*

Figure 3 (left) shows the winter distribution of baleen whale sightings and the sea bottom topography during the winter season. In general, the distribution of baleen whales in 2006 was similar to that of 2004-2005, but the number of sightings was by far lower in 2006 (214 and 47 sightings, respectively). However, the survey effort of 2004-2005 was higher than 2006 and included the main winter areas of blue whale and humpback whale aggregations.

Humpback whales were the most abundant species since they aggregate in this area during winter and, as in 2004 and 2005, they were distributed south of the study area, mainly in front of the waters of Cabo Pulmo and Los Frailes areas. However, the number of encounters is low in comparison to 2004-2005 since the surveys of the medium size boats did not include the banks “banco gorda de adentro y de afuera” (main area of the humpback whales’ concentration). Only one sighting was recorded in the Los Barriles area. This year humpback whales were not present in summer time.

Blue whale sightings in 2006 were fewer than in 2004-2005 since the search effort in 2006 was concentrated south and the study area did not include San José Island, an area where blue whales are abundant due to the *euphausiid* patches on which they feed (Croll *et al.* 1998). Bryde´s and Fin whales were sighted once in summer; but in winter Bryde’s was sighted occasionally, and probably most of the unidentified *balaenopterids* sighted (winter and summer) could belong to this species because of their evasive behavior. During the summer (Figure 3 - right) the humpback and blue whales already had begun their migration to their summer grounds, and only one sighting of blue whale was recorded (Figure 3).

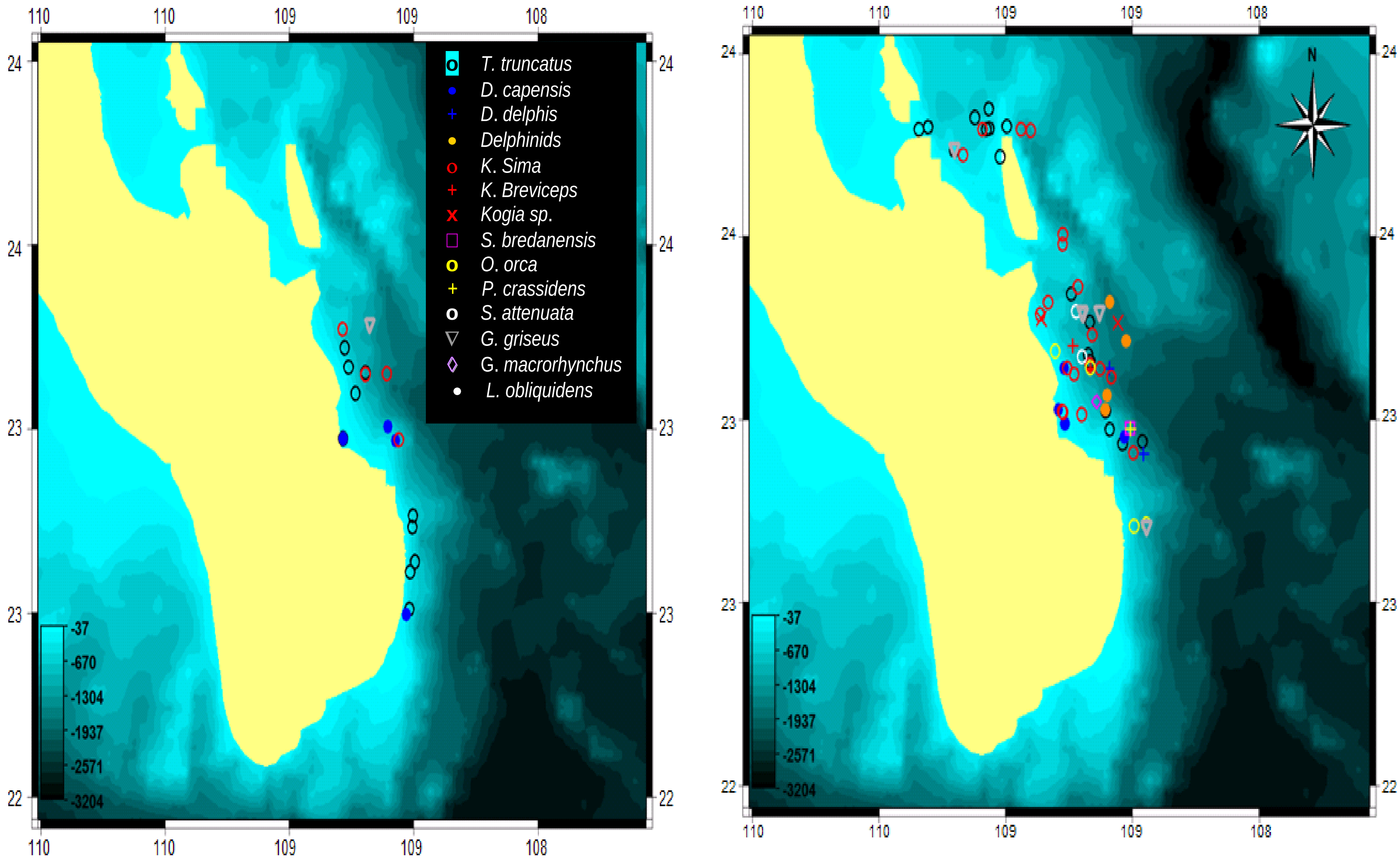

Figure 4. *Winter (left) and summer (right) sightings distribution of toothed whales (except beaked whales) in the southwestern Gulf of California (2006), and the relation with sea bottom topography. Each symbol represents a single sighting. The depth scale is in meters.*

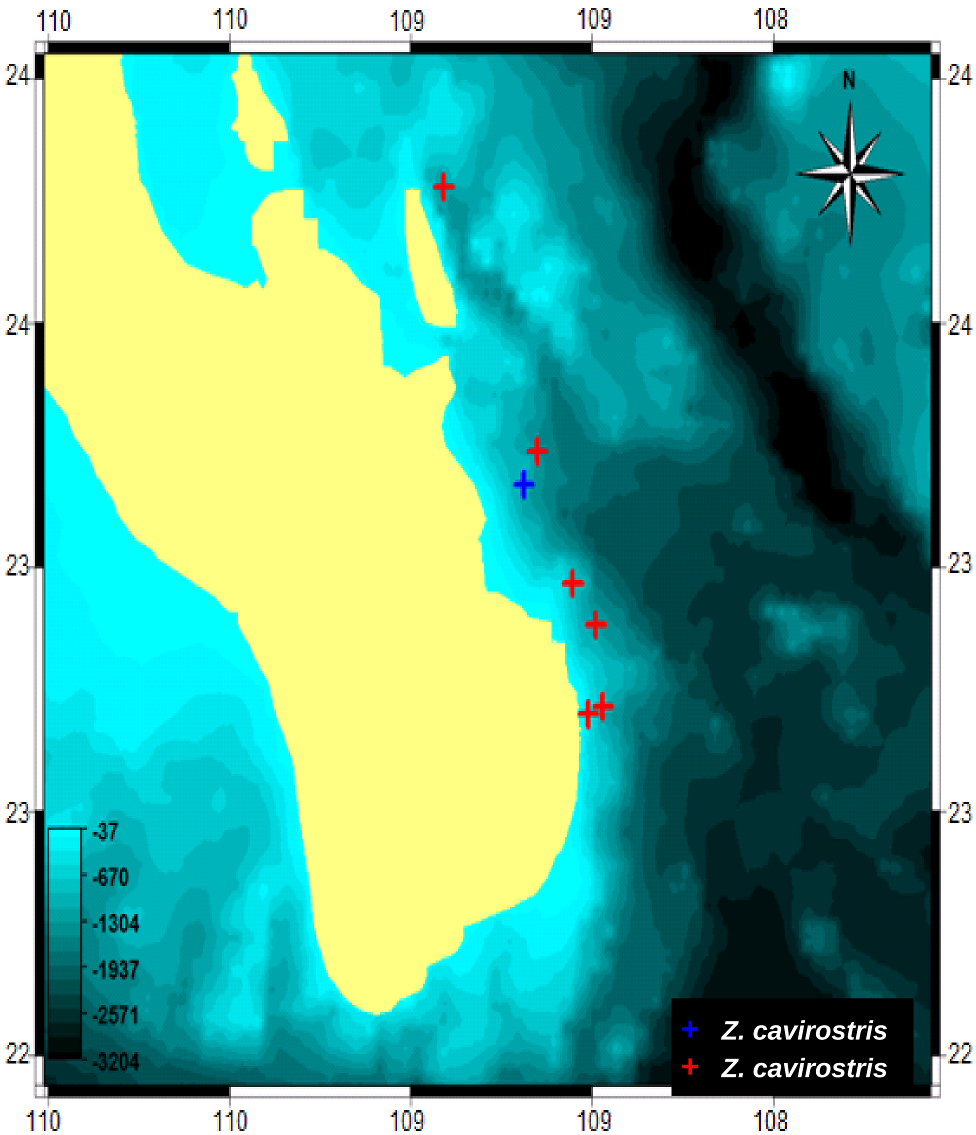

Figure 5. *Winter (blue) and summer (red) sightings distribution of beaked whales in the southwestern Gulf of California (2006), and the relation with sea bottom topography. Each symbol represents a single sighting. The depth scale is in meters.*

The species richness of toothed whales in 2006 was high, as in 2004-2005, with the same number of species (12). In 2006, Baird's and Pigmy beaked whales, sperm whales, and striped dolphins were not encountered. However, in 2006 new species were recorded for the study period, including false killer whales, rough-toothed whales, pantropical spotted dolphins, and pacific white-sided dolphins. In total, from December 2004 to December 2006 the southwest Gulf of California represents one of the areas of highest species richness of marine mammals in the world with 16 species of toothed whales and 5 species of baleen whales recorded (Table 4).

In general, the number of sightings of toothed whales in 2006 was lower than in 2004-2005 (98 and 217 sightings, respectively). During winter 2006, only 5 different species of toothed whales were recorded. Bottlenose dolphins, long beaked common dolphins and dwarf sperm whales were the most frequent and

abundant odontocetes in the area. Risso's and pacific white-sided dolphins were recorded only once (Figure 4 - left).

For the summer, there was an increase of bottlenose dolphin and dwarf sperm whale sightings, especially in May and September 2006. The increase in encounters of dwarf sperm whales in summer could be due to the presence of squid in the study area. In this season, we recorded three squid-eating species, including short finned pilot whales, pigmy sperm whales, and Risso's dolphins. However, sperm whales were not recorded in 2006 (Figure 4 – right).

In 2006, Cuvier´s beaked whale was the only species recorded for the beaked whales group and it ranked as the fourth most common toothed whale sighted (Table 4). Cuvier's beaked whales were mainly distributed in deep waters and in the continental slope. In Cabo Pulmo and Los Frailes areas, this species was recorded close to the shoreline. Six of the seven sightings were encountered between the waters in front of Punta Pescadero area and Los Frailes and were recorded in summer (Figure 5). The high number of sightings of Cuvier's beaked whales in the southwest Gulf of California suggests a resident population or a zone of transit for this species in the area.

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*SIMULATED SOUND TRANSMISSION AND RECEPTION IN CUVIER'S BEAKED WHALE (*ZIPHIUS CAVIROSTRIS*) USING THE VIBRO-ACOUSTIC TOOLBOX*

Ted W. Cranford, Petr Krysl, John A. Hildebrand

Whale strandings associated with exposure to high intensity sound have focused investigative attention on the least known cetaceans, the beaked whales. A promising technique for discovering acoustic pathways and assessing potential effects of particular sound sources involves finite element modeling (FEM). Our team has pioneered a combination of techniques to produce a flexible computational environment for acoustic simulations. We combine the anatomic geometry obtained from industrial CT scanners, tissue property measurements, and custom FEM software, the Vibro-acoustic Toolkit. Beaked whale mass stranding events have primarily involved Cuvier's beaked whale (*Ziphius cavirostris*) and we have therefore concentrated our initial efforts on them.

Simulated sound sources placed inside and outside of an adult male Cuvier's beaked whale (*Ziphius cavirostris*) have recently revealed some intriguing initial results. Sound sources located at the left and right phonic lips produce beams that converge just outside the head and slightly right of the midline. This result supports the notion that dual sonar sources interfere constructively to form a sonar beam in front of the animal. This is consistent with how the biosonar system works in the bottlenose dolphin as we currently understand it (Cranford & Amundin 2003).

The most important and pertinent questions to answer are those that attempt to understand how, or by which pathways, sounds reach the hearing apparatus. The simulations that address this question have produced the most intriguing results thus far because they do not align with the leading ideas about how this system functions. In 1968, Norris proposed that echoes returning from a target enter the head through a fatty pad (the acoustic window) external to the mandible. Then, according to Norris, sound passed through the thinned posterior wall of the lower jaw, and propagated through the internal mandibular fat bodies to the bony ear (tympanoperiotic) complexes. Our tests indicate that sound pressure waves may also travel along a novel pathway, entering the head from below and between the lower jaws and then continuing toward the bony ear complexes through the internal mandibular fat bodies. This does not negate the conventional understanding but changes it irrevocably.

Our digital library of CT scans was expanded during 2006-2007 with additional species of beaked whales and an additional specimen of killer whale. To efficiently process and scan these specimens we designed and built a special container to hold multiple beaked whale heads for scanning. Likewise we built a container and encased a new killer whale specimen for scanning. The CT scans were conducted and we have begun processing scan data in preparation for segmentation. The value of the Vibro-acoustic Toolkit approach increases with the taxonomic expansion of the digital library of cetacean anatomy. Finite element modeling facilitates investigations of acoustic exposure across a broad spectrum of species, which may include non-mammalian vertebrates in the future.

During 2006-2007 two manuscripts were published (Krysl *et al.* 2006, McKenna *et al.* 2007) and three manuscripts were submitted for publication (Cranford et al. In Press, Cranford et al. In Review, Krysl *et al.* In Press). In addition, preliminary results from Cuvier's beaked whale (*Ziphius cavirostris*) simulations were presented at the conference on the Effects of Noise on Aquatic Life in Nyborg, Denmark.

OBJECTIVES

The primary aim of this effort is to build a "vibro-acoustic simulator" that can be used to answer basic questions and test new ideas about how sound propagates through the heads and bodies of cetaceans.

Proximal Goals:

- Develop FEM simulations of sound propagation using the entire head of a neonate *Ziphius cavirostris* from our current library.
- Increase taxonomic breadth of digital library of cetacean CT scans. Collect additional specimens and conduct CT and MR scans, as well as measure properties of various tissues and organs from those specimens.
- Develop Vibro-acoustic Toolkit to perform FEM simulations.
- Develop processes and algorithms that can be used to transform remote imaging data into a format that can be used in the library and manipulated to serve as input for FEM simulation software.
- Use simulator to predict received sound levels and acoustic waveforms at the tympanoperiotic complex and other organs and structures within the head.
- Compare FEM simulations for frozen vs. thawed scans of neonate *Ziphius* head.
- Measure shear-wave velocity (this is an important tissue property that needs to be included in the simulator).

Long Term Goals:

- Evaluate efficacy of FEM simulations of the sound propagation into the tympanoperiotic complex in an adult *Ziphius*, including coupling of middle and inner ear of the cochlea (by comparisons with *Tursiops*).
- Collect data on live dolphins to augment and compare with existing data for validating FE simulations and extrapolation to postmortem specimens.
- Develop technique and/or devices to measure shear waves.
- Develop ability to measure magnetic resonance elastography and compare with shear wave velocities.

METHODS

The vibro-acoustic simulator combines CT scan information and tissue property measurements with finite element modeling (FEM) software to simulate sound propagation pathways into and out of the specimens represented in the scans. This study capitalizes on the recent availability of industrial CT scanners to collect data from postmortem whales. Our team has pioneered a valuable innovation, combining anatomic geometry obtained from CT scans with tissue property measurements and custom FEM software to produce a flexible computational environment for acoustic simulations (Krysl *et al.* 2006).

Over the past ten years, one of us (Cranford) has developed and tested a technique to scan large cetacean specimens (Cranford 1999). Once obtained, the CT scans make possible a host of research efforts. Foremost in this effort is the advancement of our understanding of the interaction between sound and the anatomy of a whale.

The specimens are placed in a registration frame, frozen to preserve tissue quality, and scanned. After scanning, the specimens are thawed, sampled, and tissue properties measured. This sequence of steps has been used successfully in past efforts. After scanning, specimens are dissected so that tissue properties

can be measured and recorded. These values can then be added to the density information given by the scanning process to form the geometric model of the whale.

Methodological Advancements

To test possible gains in cost savings during scanning, while maintaining image quality, an attempt was made to scan multiple specimens at the same time by encasing them in the same scanning tube. At the writing of this report, the scan data are not yet available, but preliminary feedback indicates that the results were positive.

Methodological Evaluation

As part of the process of validating our methodological procedures we compared CT data from live, frozen, and thawed specimens of *Tursiops truncatus* (McKenna *et al.* 2007). This study shows that CT scanning produces similar results in tissues and organs for the following quantities: geometry, absolute density, and sound velocity across all specimens. These results imply that the viscoelastic properties for this species across treatment classes provide a solid basis for building accurate simulations of sound propagation based upon postmortem specimens. Additional evaluation studies are scheduled.

Development of The Vibro-Acoustic Toolkit

The next step in this project was to assemble a finite element model (FEM) to simulate/predict sound propagation pathways in our scanned specimens. Building, testing and refining the FEM software is an iterative process that relies on validation, feedback, and continues throughout the project.

A comprehensive formulation for vibro-acoustic problems in medicine and biology has been developed as part of this research (Krysl *et al.* In Press). To address the difficult problem of discretizing anatomical geometries, the mesh is voxel-based, and is generated automatically from common biomedical data sets (CT scans and MRI). A fully Lagrangian finite element formulation based on the decomposition of incident and scattered fields has been developed to incorporate seamless coupling of fluids and viscoelastic solids, and to allow for accurate representation of incident acoustic excitation.

The superposition principle is used to separate the incident acoustic wave from the scattered and radiated waves in a displacement-based finite element model. An absorbing boundary condition is applied to the perturbation part of the displacement. Linear constitutive equation allows for inhomogeneous, anisotropic materials, both fluids and solids. Displacement-based finite elements are used for all materials in the computational volume. Robust performance for materials with limited compressibility is achieved using assumed-strain nodally-integrated simplex elements or incompatible-mode brick elements. A centered-difference time-stepping algorithm is formulated to handle general damping accurately and efficiently. A highly efficient parallel finite element code has been written, and an eight processor Linux machine enabled simulations with ~1/2 billion unknowns to be carried out within a matter of days.

ACCOMPLISHMENTS FOR FY 2006-2007

1st Quarter

- Survey available specimens and arrange transfer of the most appropriate ones to San Diego.
- Probe FEM simulation space of Cuvier's beaked whale (*Ziphius cavirostris*) for source locations and sound reception characteristics.
- Feedback and iteration with Krysl on refinements, improvements, and new functionality to FEM code.

2nd Quarter

- Continue FEM simulations of *Ziphius cavirostris*.
- Ship Sowerby's and Blainville's beaked whale and killer whale specimens to San Diego.
- Begin segmentation of previously scanned killer whale (*Orcinus orca*) CT scans.

3rd Quarter

- Design and build special container to hold multiple beaked whale heads for scanning.
- Build container and encase new killer whale specimen.
- Conduct CT scans of beaked whales and killer whale at Hill AFB.
- Discover convergent interference beam pattern for bilateral sound sources in *Ziphius* using FEM simulations.
- Discover novel pathway for sound entering the head and traveling to the ear complexes in *Ziphius* using FEM simulations.

4th Quarter

- Feedback to Krysl for iterative refinements, improvements, and needed functionality to FEM code.
- Process scan data from specimens scanned at Hill AFB in preparation for segmentation.
- Plan presentation of preliminary results from Cuvier's beaked whale (*Ziphius cavirostris*) simulations at the conference on the Effects of Noise on Aquatic Life in Nyborg, Denmark.

SUMMARY OF RESULTS

The cephalic anatomy of toothed whales is marked by structural complexes that have long been recognized as components of a sophisticated biosonar system. This sonar system has three categorical divisions: the sound generation and transmission apparatus, the sound reception and transduction apparatus, and the central nervous system components that control output and interpret input.

Sound Generation and Transmission

The sound generation and transmission apparatus is composed primarily of structures that are nasal in origin. The comparative anatomy of this region has been studied in some detail across the entire odontocete suborder (Norris 1964, Norris *et al.* 1961, Cranford 1999, Cranford *et al.* 1996, Mead 1975, Heyning 1989). Only in recent years have we been able to nail down the site and generation mechanism for sonar signals in bottlenose dolphins (Cranford 2000, Cranford & Amundin 2003). We can only speculate about whether other odontocetes are using homologous structures and similar means.

The nasal apparatus in all odontocetes is unlike that in any other mammal, being greatly enlarged, fitted with specialized lipid organs, and skull bones sculpted into an amphitheater-like shape. What we know about these specialized tissue structures has been reviewed in Cranford and Amundin (2003). We have a reasonable idea about the structure/function of nasal complex for a handful of odontocetes. If we compare the simulations for the sound generation and transmission anatomy in *Ziphius* with those of *Tursiops truncatus* and *Phocoena phocoena*, the acoustic beams formed are similar in shape and direction.

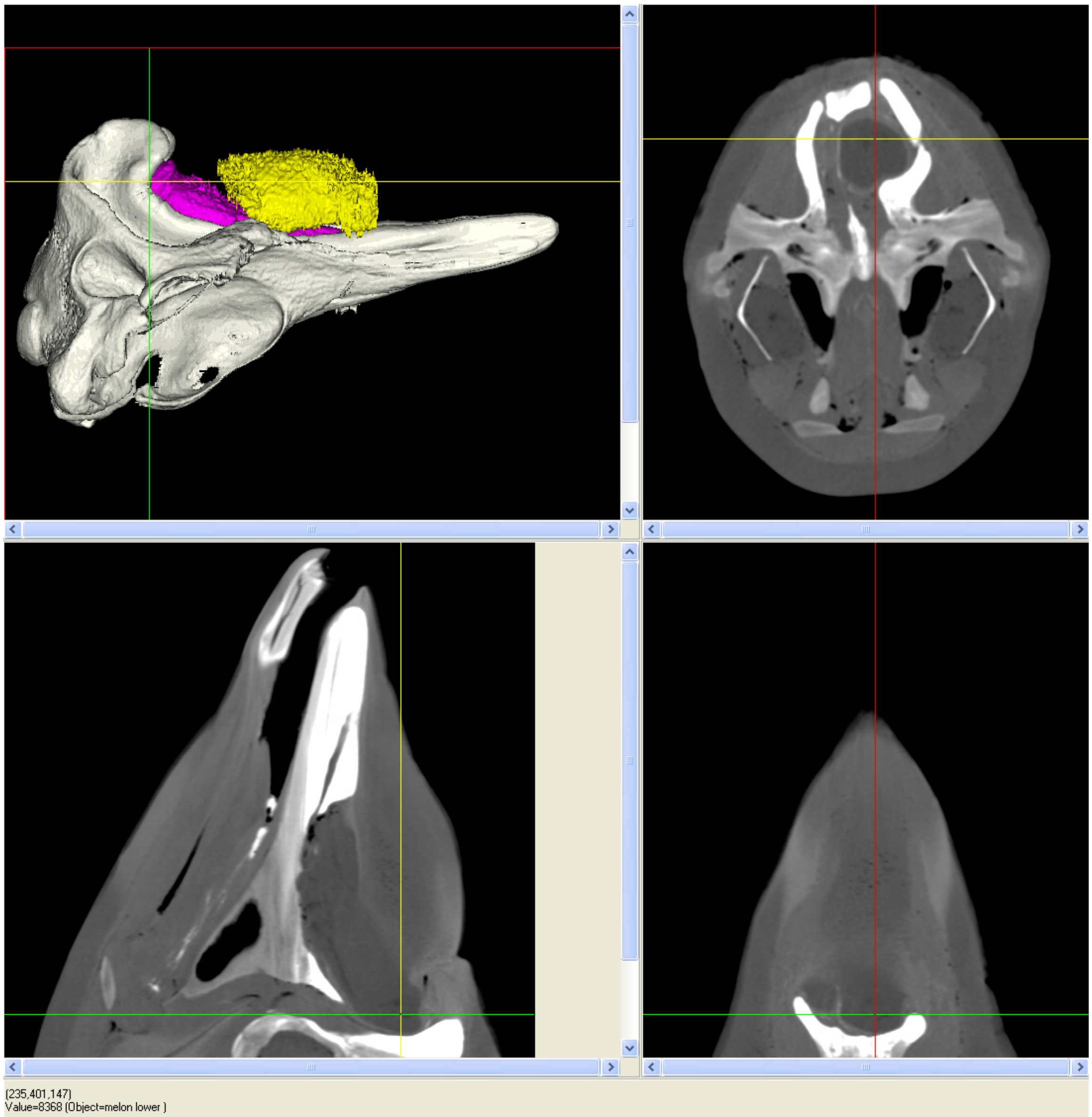

Figure 6. *The top left image is a pseudo 3-D view of the skull and the primary lipid structures of the forehead in* Ziphius cavirostris. *The top right image is a transverse section whose location is indicated by the green lines. The bottom left image is a sagittal section whose location is indicated by the red lines. The bottom right image represents a horizontal section whose location is indicated by the yellow lines. The point of intersection (235, 401, 147) between the planes (and lines) represents the location of the sound source for simulations beginning at or near the phonic lips on the right side of the animal.*

A source placed at the phonic lips to the right of the nasal septum (Figure 6) produces a beam that emerges from the head slightly to the right of the midline (Figure 7). It is intriguing that a source placed at the complimentary location, the phonic lips to the left of the nasal septum, also produces an acoustic pressure beam that emerges from the head to the right of the midline (Figure 2). These simulations support the notion that if sounds were generated at both (left and right) phonic lips at the same (or nearly the same) time, they could converge into a beam that is more intense than either of the sources due to constructive interference. This is the kind of information that has never been verified for other

odontocetes, even though a few workers have suspected that this is the case. When we move to simulations of other odontocetes we will be able to test whether it holds true and suggests a concept that is broadly applicable.

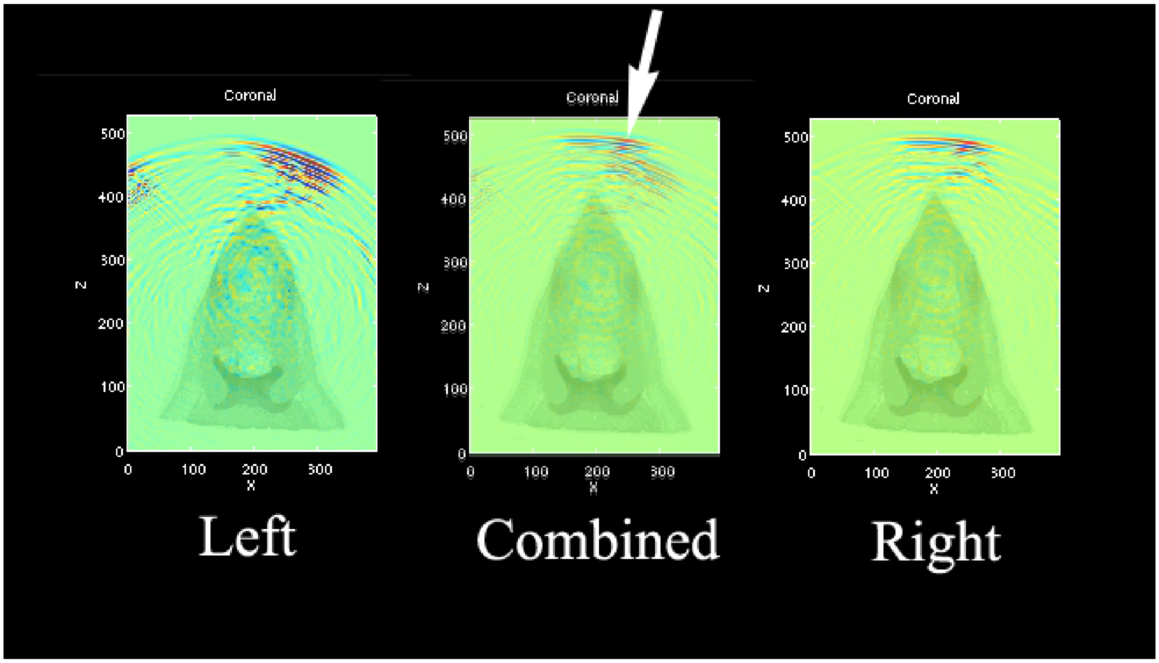

Figure 7. *Example of the formation of an interference transmission beam. Two separate simulations were generated, one with the source located at the left phonic lips (Left) and the other with the source located at the right phonic lips (Right). The center panel (Combined) shows the combination of the panels on either side. The panels represent similar horizontal planes through the simulation space. The white arrow shows the region where the beams from each simulation overlap.*

Similar results are obtained even when tissue properties are changed by 5% or more. This is similar to the results obtained by Aroyan, Cranford et al. (Aroyan *et al.* 1992) and supports the notion that the geometry of tissue structures and their interfaces are more important factors in beam formation than any slight variation in tissue properties.

In addition, an acoustic waveguide lined with pachyosteosclerotic bones is apparently part of a novel transmission path for outgoing biosonar signals in deep diving animals. These newly described transmission pathways are reminiscent of the configuration that would be seen in a sperm whale with its forehead turned upside-down.

Laryngeal Sound Source

Originally, it was assumed that the source of odontocete sonar signals was located in the larynx. The "laryngeal phonation hypothesis" was put forward largely based on anatomic evidence and a debate raged in the literature for two decades (see review in Cranford and Amundin 2003). The experimental evidence called this notion into question beginning in the 1980's. Our FEM simulations indicate that a sound source in the larynx could not produce a useful, forwardly directed sound beam in *Ziphius*.

Sound Reception Pathways

Hearing is the culmination of a set of complex processes. In odontocetes, it involves a directivity index that is frequency dependent and structurally mediated; filtering, focusing and transduction, which are also structurally mediated; and central nervous system processing. Most of what we know about hearing in odontocetes is the result of study and experimentation with a single species, the bottlenose dolphin (*Tursiops truncatus*). Any extrapolation from the results of work with *Tursiops* to any other species should be undertaken with extreme caution. At the same time, any results that are the same or similar between disparate species may indicate similarity in the structure/function paradigm and phylogenetic origin.

Our FEM studies provide a window into structurally mediated processes, which result from the complex interactions between sounds and anatomic structure. Simply put, we can, for the first time, model and simulate acoustic pathways in odontocetes. By contrast, the vast majority of prior acoustic research into odontocetes is often based upon complex functions as a whole, rather than teasing apart or isolating various aspects of it. The application of FEM allows us to ask questions that consider systems of structures or their isolated contributions.

Where does sound enter the head of odontocetes? This seemingly simple question has not been satisfactorily delineated for any odontocete. In 1968, Norris proposed that echoes returning from a target enter the odontocete head through a fatty pad (the acoustic window) external to the mandibles. Then, according to Norris, sound passed through the thinned posterior wall of the lower jaw, and propagated through the internal mandibular fat bodies to the bony ear (tympanoperiotic) complexes, a process known as "jaw hearing." Jaw hearing is based primarily upon anatomy and a group of psychoacoustic experiments. Perhaps the most foremost among them is the exquisite work of Brill and his colleagues (Brill and Harder 1991). Our studies indicate that the notion of jaw hearing needs refinement in light of recent results combined with seemingly odd results from the literature.

In addition to jaw hearing, our studies indicate that sound reception may also occur by way of a novel pathway, through the oral cavity (Figure 8). A simulated 40 kHz planar pressure (p) wave approaches the animal with an angle of incidence of zero degrees (above the horizontal). When the acoustic pressure wave encounters the cone of soft tissues surrounding the head; it refracts around, largely below, and between the mandibles; enters the internal mandibular fat body; and propagates caudally to the bony ear complex (Figure 9). This is a novel acoustic pathway to the ears that to our knowledge has not been sufficiently considered.

The intensity of the p waves that reach the bony ear complexes are dependent upon angle of incidence. As the source rises above the horizontal, the intensity of the signal reaching the ears is diminished. Frequency filtering, if it occurs along this new pathway, is not immediately obvious and will be the subject of further investigation.

There are a couple of tidbits of evidence in the literature that suggest a similar pathway exists in the bottlenose dolphin and may be extrapolated to all other odontocetes. Curiously, even though Møhl and his colleagues (Møhl *et al.* 1999) measured a region of high (acoustic) sensitivity along the ventral midline in a bottlenose dolphin, they did not comment on this interesting result. We surmise that this unique result for *Tursiops* supports our preliminary results for *Ziphius*, suggesting a broad taxonomic implication. Interestingly, Møhl and his colleagues (1999) also found that the most sensitive region for sound entering the head was slightly forward of the conventional understanding of the acoustic window.

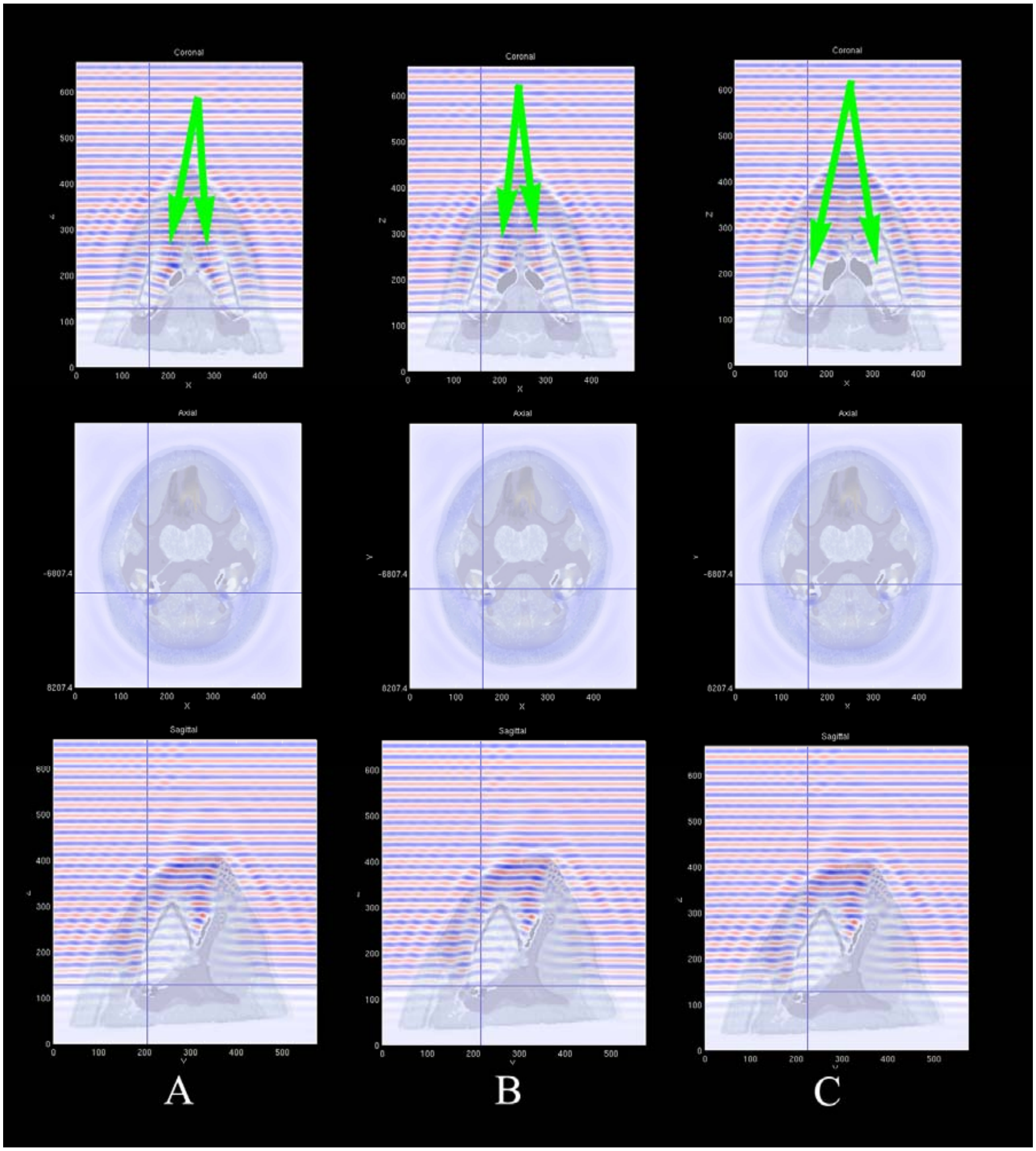

Figure 8. *A new pathway to the hearing apparatus from in front of* Ziphius *is suggested. Each column of images represents three intersecting planes in the simulation space. The lowest plane is in column A, the middle plane is in column B, and the highest plane is in column C. The thin blue lines in each image show the location of the other images in that column. The new hearing path is most easily seen along the top row (horizontal planes), where the waves are shown being channeled back to the ear complexes (indicated by green arrows).*

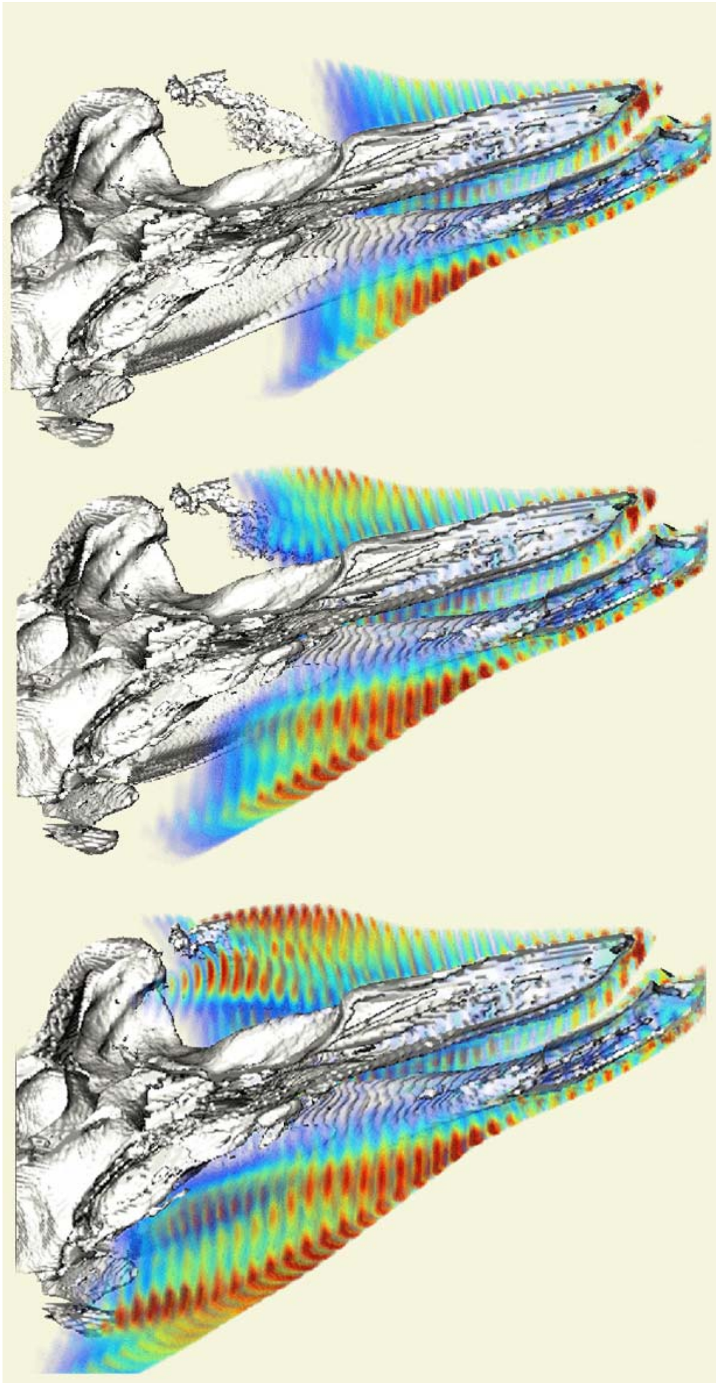

Figure 9. *These three panels represent frames from an acoustic FEM simulation showing displacement amplitude. In this case, a 40 kHz planar wave was incident upon the specimen from directly in front and zero degrees above the horizontal. In order to facilitate viewing of the propagation process, the right side of the specimen has been removed during the rendering of the movie, but after the original simulation. Note that the colored waves wrap around (refract) the ventral margin of the mandible, enter the fatty channel on the inside of the mandible, and propagate back to the bony ear complex.*

Our simulations suggest an explanation, the theoretical basis of which occurred to Møhl and his colleagues:

> *"When evaluating the models, it should be borne in mind that the cross section of the mandible is on the same order of magnitude as the dominant wavelength of p-waves (compressional or longitudinal waves, as opposed to transversal and shear waves) in water and soft tissues at 50 kHz (3 cm). A logical consequence of this observation is that models inspired from optical analogies (reflections, refraction, etc.) are problematic, as they require structures that are considerably larger than the wavelength. However, in mixed media with solid components, other sorts of waves than compressional, longitudinal ones can be realized." (Møhl* et al. *1999, page 3424)*

Their proposition that combinations of wave types are likely to be operational in mixed media containing solid components, is in line with what we see in the FEM simulations. One possible explanation is that pressure (p) waves and shear (s) waves combine to form flexural waves within the thinned bony region of the posterior mandible. These flexural waves will allow sound to propagate into the internal mandibular fat bodies on the way to the bony ear complexes. This flexural wave mechanism can cause filtering to occur by preferentially passing frequencies according to the thickness of the bony shell plus the stiffness or elastic properties of the bone. In addition, the "C" shaped (in X-section) mandible changes gradually in thickness and may therefore pass certain frequencies (e.g., filtering) according to the parameters of mandibular structure and the acoustic signal incident upon it. Figure 10 shows the frequency response of the jaw at various stations. Note that there is a distinct peak near 40 kHz, which is the peak frequency of signals measured from these animals in the wild (Zimmer *et al.* 2005).

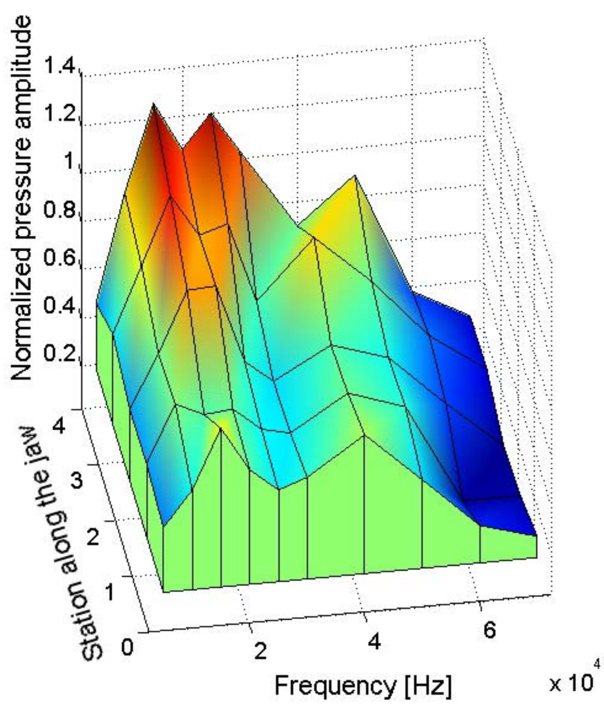

Figure 10. *Graph of the normalized pressure along the jaw (0 is anterior) as a function of frequency (10 – 70 kHz).*

The current crop of simulations allows us to predict the time delay and the difference in intensity between the ear complexes, due in large part to shielding by a suite of anatomic structures (Figure 11). More specifically, simulations containing the juxtaposition of the large pterygoid sinuses, a fibrous venous plexus, and lipid-rich pathways that connect the acoustic environment to the bony ear complex provide a means for understanding and delineating the specific contributors to interaural differences. We can also use the vibro-acoustic simulator to predict changes to acoustic waveforms at any point in the simulation space as a result of the complex interactions of other organs and structures within the head.

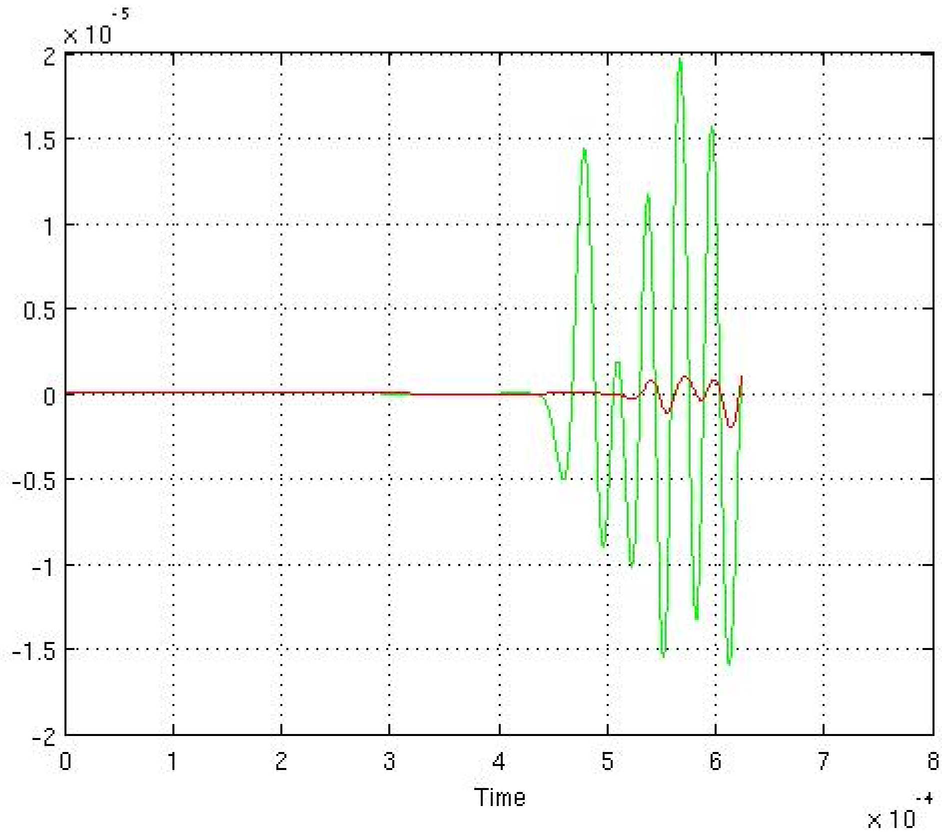

Figure 11. *Acoustic shadowing is demonstrated in records of acoustic pressure at the intersection between each tympanoperiotic complex and the corresponding internal mandibular fat body attached to it. The source was located a few degrees to the left and in front of the head. The green trace shows that the acoustic pressure wave at the left ear arrives earlier in time and with greater amplitude. The red trace shows that a collection of anatomic structures shield the right ear complex, so that the sound pressure wave arrives later and lower in amplitude.*

Our simulations support a new acoustic pathway to the ears from under the mandibles, and the notion of a flexural wave that offers a plausible explanation for the conventional pathway through the thinned mandibles as originally described by Norris (1968).

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PROJECT PUBLICATIONS

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CRANFORD, T. W., M. MCKENNA, M. SOLDEVILLA, S. M. WIGGINS, R. SHADWICK, J. GOLDBOGEN, P. KRYSL, J. S. LEGER and J. A. HILDEBRAND. In Press. Anatomic geometry of sound transmission and reception in Cuvier's beaked whale (Ziphius cavirostris). *Anatomical Record*.

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ABSTRACTS

Cranford, T.W., P. Krysl, and J.A. Hildebrand (2007). Sound Propagation in Cuvier's Beaked Whale (*Ziphius cavirostris*): A Test Case for Simulating Sound Propagation in Aquatic Organisms using FEM. Conference on the Effects of Noise on Aquatic Life, Nyborg, Denmark.

Cranford, T.W., P. Krysl, and J.A. Hildebrand (2007). Sound pathways revealed: Simulated Sound Transmission and Reception in *Ziphius cavirostris*. 17th Biennial Conference on the Biology of Marine Mammals, Cape Town, South Africa.

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